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A Matheuristic for the Cargo Mix Problem

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1 Introduction

Container liner shipping is the most economically friendly mode of transport, with the lowest CO2 emission per tonne-km. It is, however, an industry goal that the CO2 emission should be reduced by 20% per tonne-km by 2020 compared to 2011. This constitutes a big challenge: It is technically hard to find viable alternatives to fossil fuels, moreover it is hard to convince a competitive industry to pay for cleaner transport since this is not visible to the end customers, and therefore cannot justify a higher cost. Hence, optimization may be one of the few options to reach the 2020 industry goal. A possible direction is to focus on vessel' utilization. A better utilization will result both in cleaner transport and in better revenue margins.

Delgado (2013) introduces the *cargo-mix* (or cargo composition) problem which aims at identifying a composition of container types to be loaded on a vessel during its journey. The problem targets a set of standard container types defined by their length (20', 40' or 45'), weight and category (dry, reefer or high-cube). Delgado (2013) assume that for a given set of ports, a minimum cargo load requirement exists, which reflects static capacity contracts. The loaded containers must satisfy the same stacking and stability requirements of stowage planning problems (e.g. Pacino et al. (2011), Ambrosino et al. (2015), Kang and Kim (2002), Wilson and Roach (1999)). Stacking constraints include, among others, the assignment of reefer containers near reefer plugs, stack weight and height limit requirements, and disallowing 20' containers to be stowed on top of 40' ones. Stability constraints ensure that the vessel is seaworthy, meaning that its *draft* (the underwater depth reached by the vessel) respects each port limitation and that vessel *trim* (the longitudinal inclination angle) and *stress forces* (shear forces and bending moments) are within operational limits. As noted by Delgado (2013) and Pacino et al. (2012), since the cargo load is not known, the *displacement* (total weight of the vessel) is variable, which implies the use of linearization

techniques to handle stability constraints.

The rich number of industrial constraints included in the model, allows the approach to give decision makers a reliable tool to analyze the impact each container has on the overall intake or revenue of the vessel. Experimental evaluation by Delgado (2013) has shown that a relaxation of the industrial requirements results in a large overestimation of the capacity. Delgado (2013) proposed an IP formulation that, however, cannot scale to multi-port analysis. The authors thus applied a decomposition approach inspired by the work of Pacino et al. (2011) on stowage planning.

In our work, we wish to extend the problem described by Delgado (2013) by modeling a full cyclic service (rather than a set of ports) and by constraining the available cargo with a set of expected cargo flows. Moreover, we include *block stowage* constraints which makes the problem close to what is done in the industry, but which also greatly increases its complexity. Block stowage was first introduced in the literature by Ambrosino et al. (2015), and it requires the division of the vessel into blocks corresponding with the position of the *hatch-covers* (metallic structures that divide the upper and lower deck). Containers within a block are all forced to have the same port of discharge. This effectively adds a new decision to the problem, the assignment of discharge ports to a block, thus all the assignments for a given block can be seen as a schedule of discharge ports. We use this idea of a schedule to propose a novel compact formulation of this problem and a heuristic procedure based on a 3-phase hierarchical decomposition.

2 Compact model and solution approach

We present the core of our compact model for the cargo-mix problem with block stowage. We use a 4 index formulation where $y_b^{ct} \in \mathbb{Z}_+$ indicates the number of containers of type $c \in \mathcal{C}$ to be stowed in block $b \in \mathcal{B}$ during transport \mathcal{T} . A transport is a pair of origin and destination ports (hence the 4 index formulation). The model is as follows:

$$\text{Max } z = \sum_{b \in \mathcal{B}} \sum_{c \in \mathcal{C}} \sum_{t \in \mathcal{T}} f(c, t) y_b^{ct} \quad (1)$$

s. t.

$$\sum_{t \in \mathcal{T}_p^{On}} \sum_{c \in \mathcal{C}} v^c y_b^{tc} = w_{bp} \quad \forall b \in \mathcal{B}, p \in \mathcal{P} \quad (2)$$

$$y_b^{tc} \leq M \sigma_{bp}^{d(t)} \quad \forall b \in \mathcal{B}, c \in \mathcal{C}, p \in \mathcal{P}, t \in \mathcal{T}_p^{On} \quad (3)$$

$$\mathbf{w} \in \mathcal{W} \quad (4)$$

$$\mathbf{y} \in \mathcal{K} \quad (5)$$

The objective (1), maximize the intake of the vessel based on a function ($f(c, t)$) of transport and cargo type (e.g. TEU intake or revenue). Constraint (2) defines the weight variable w_{bp} for each block $b \in \mathcal{B}$ and port $p \in \mathcal{P}$. In (3), the variable σ_{bp}^d defines if discharge port d is assigned to block $b \in \mathcal{B}$ at port $p \in \mathcal{P}$, where \mathcal{T}_p^{On} is the set of all transports traversing port p , and $d(t)$ is the discharge port of transport t . For the sake

of simplicity, in (4) and (5), we define \mathbf{w} and \mathbf{y} , respectively the set of all the w and y variables. The constraints then imposes the their value must be within the polyhedral defined by all the stability constraints \mathcal{W} and capacity constraints \mathcal{K} of the problem.

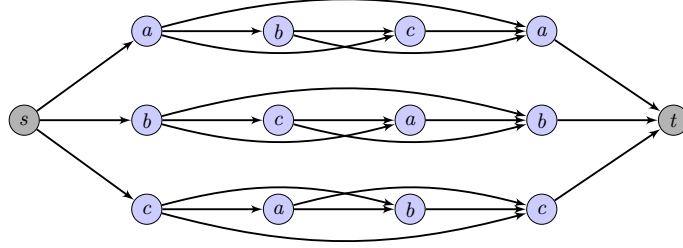


Figure 1: An example graph with 3 ports.

The compact model can hardly be solved for instances of more than one port. Thus, we propose a 3-phase heuristic procedure. The **first phase**, heuristically finds values for the σ_{bp}^d variables. Given a block b , the value of the variables can be thought of as a schedule for block b . We represent all the possible schedules as a directed acyclic graph, where the nodes represents the visited ports and the arcs the possible sequential paths (an example with 3 ports is show in Figure 1). We solve a longest path problem over the graph where each arc has a weight based on the maximum number of containers that can be transported on that arc.

Let $\hat{\sigma}_{bp}^d \quad \forall b \in \mathcal{B}, p \in \mathcal{P}, d \in \mathcal{P}$ be the solution from the first phase. The **second phase** solves a relaxed version of the original model where (2) is substituted with

$$\sum_{t \in \mathcal{T}_p^{O^n}} \sum_{c \in \mathcal{C}} v^c y_b^{tc} \leq w_{bp} \quad \forall b \in \mathcal{B}, p \in \mathcal{P} \quad (6)$$

and where we impose

$$\sigma_{bp}^d = \hat{\sigma}_{bp}^d \quad \forall b \in \mathcal{B}, c \in \mathcal{C}, p \in \mathcal{P}, p \in \mathcal{P} \quad (7)$$

The relaxation of the weight constraint allows the model to solve much quicker. Due to the relaxation of the weight constraints, solutions from the second phase might still be infeasible in terms of stability. The **third phase** addresses this issue by finding a feasible solution that removes the least amount of containers. Let $\hat{y}_b^{tc} \quad \forall t \in \mathcal{T}, c \in \mathcal{C}, b \in \mathcal{B}$ be the solution of the second phase, we solve the following model:

$$\text{Max } z = \sum_{b \in \mathcal{B}} \sum_{c \in \mathcal{C}} \sum_{t \in \mathcal{T}} f(c, t) (\hat{y}_b^{ct} - u_b^{tc}) \quad (8)$$

s. t.

$$\sum_{t \in \mathcal{T}_p^{O^n}} \sum_{c \in \mathcal{C}} v^c (\hat{y}_b^{tc} - u_b^{tc}) = w_{bp} \quad \forall b \in \mathcal{B}, p \in \mathcal{P} \quad (9)$$

$$\mathbf{w} \in \mathcal{W} \quad (10)$$

$$u_b^{tc} \leq \hat{y}_b^{tc} \quad \forall b \in \mathcal{B}, t \in \mathcal{T}, c \in \mathcal{C} \quad (11)$$

The model is a variation of the original formulation, where the variable u_b^{tc} represents the number of containers of type $c \in \mathcal{C}$ to be removed from block $b \in \mathcal{B}$ during transport $t \in \mathcal{T}$. It is fair to assume that any stability issue an empty vessel might face can be fixed with ballast water. Thus the model will always find a feasible solution.

3 Preliminary Results

The preliminary result is summarized in Table 1. The vessel used has a capacity of $\sim 15,000$ TEU's. 170 instance have been generated, with a varying number of ports, ranging from 4 to 20. The instances are divided into 17 instance classes, depending on the number of ports in the instance. In the table below, $|P|$ is the number of ports in the instance class, n is the number of instances in the class. \bar{t}^c is the average time for the compact model to solve the instance, and \bar{x}^c is average the gap to a computed upper bound. \bar{t}^h and \bar{x}^h is the averages for the heuristic. For the compact model a timelimit of 3600 seconds were used and '-' denotes that no feasible solution were found.

$ P $	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
n	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
\bar{t}^c	2958	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600
\bar{x}^c	12%	11%	50%	62%	60%	59%	62%	-	-	-	-	-	-	-	-	-	-
\bar{t}^h	1	2	2	4	5	8	8	10	14	22	15	19	23	23	36	28	31
\bar{x}^h	8%	10%	10%	10%	12%	10%	11%	13%	13%	13%	12%	12%	12%	11%	11%	11%	10%

Table 1: *Results for the matheuristic.*

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